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Postprint: Species Diversity of Understory Plant Communities in Robinia pseudoacacia Forests with Different Densities in the Loess Region of Western Shanxi

Authors: Wang Siqi1, Zhang Jianjun[1],[2],[3], , Zhang Yanqin 5, Zhao Jiongchang 1, Hu Yaowei1, Li Yang 1, Tang Peng1, Wei Zhaoyang1

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Abstract

Stand density exerts significant influence on understory plant community structure and species diversity in Robinia pseudoacacia forests. Clarifying the variations in understory plant community structure and species diversity under different stand densities is conducive to vegetation restoration and enhancement of forest ecological functions in the Loess region. This study investigated the community composition characteristics, growth characteristics, and species diversity of understory plants in Robinia pseudoacacia plantations in the Loess region of western Shanxi through field surveys across six stand densities (950 trees · hm^{-2}, 1450 trees · hm^{-2}, 1950 trees · hm^{-2}, 2450 trees · hm^{-2}, 2950 trees · hm^{-2}, 3450 trees · hm^{-2}). The results showed: (1) Understory plants in the study area comprised a total of 77 species belonging to 65 genera and 39 families, including 36 shrub species from 29 genera and 16 families, and 41 herb species from 36 genera and 25 families. Shrub layer species richness peaked at a stand density of 1950 trees · hm^{-2}, while herb layer species richness peaked at 2450 trees · hm^{-2}. The understory plant communities of Robinia pseudoacacia were dominated by species from Rosaceae, Compositae, Gramineae, and Caprifoliaceae. With increasing stand density, the dominant species transitioned from heliophytic and mesophytic species to sciophytic species. (2) In Robinia pseudoacacia forests, shrub height and aboveground biomass decreased with increasing stand density, while herbaceous aboveground biomass showed no significant differences among stand densities ($P > 0.05$), and the total coverage of shrub-herb communities varied only slightly. (3) With increasing stand density of Robinia pseudoacacia, the Margalef richness index and Shannon-Wiener diversity index of the shrub layer exhibited a trend of initial increase followed by decrease, reaching their maximum at a stand density of 1950 trees · hm^{-2}, while the Simpson dominance index and Pielou evenness index showed a gradually decreasing trend. The Margalef richness index and Shannon-Wiener diversity index of the herb layer reached their maximum at a stand density of 2450 trees · hm^{-2}, while the Simpson dominance index and Pielou evenness index peaked at a stand density of 1950 trees · hm^{-2}. (4) The similarity in species composition of understory plant communities under different densities of Robinia pseudoacacia reached moderate similarity or higher. When stand density was 1950–2450 trees · hm^{-2}, the species diversity of understory plant communities in Robinia pseudoacacia forests was optimal, which is conducive to the enhancement and sustainable functioning of its ecological functions.

Full Text

Abstract

Stand density has an important effect on understory plant community structure and species diversity of *Robinia pseudoacacia* plantations. Identifying changes in understory plant community structure and species diversity under different stand densities is helpful for vegetation restoration and improving forest ecological function in loess regions. Taking a *R. pseudoacacia* plantation in the loess area of western Shanxi as the research object, we analyzed understory community composition characteristics, growth characteristics, and species diversity associated with six stand densities (950, 1450, 1950, 2450, 2950, and 3450 trees · hm^{-2}) through field investigation. The results showed that: (1) A total of 77 understory plant species were identified, belonging to 65 genera in 39 families, including 36 shrub species from 29 genera in 16 families, and 41 herb species from 36 genera in 25 families. The number of shrub layer species peaked at a stand density of 1950 trees · hm^{-2}, while the number of herb layer species peaked at 2450 trees · hm^{-2}. The understory community of *R. pseudoacacia* forest mainly consisted of Rosaceae, Compositae, Gramineae, and Caprifoliaceae species. With increasing stand density, the dominant species transitioned from heliophytic and mesophytic species to shade-tolerant species. (2) The height and aboveground biomass of shrubs decreased with increasing stand density. The aboveground biomass of the herb layer showed no significant difference among stand densities ($P > 0.05$), and the total coverage of shrub and herb communities changed little. (3) With increasing stand density, the Margalef richness index and Shannon-Wiener diversity index of the shrub layer first increased and then decreased, peaking at a stand density of 1950 trees · hm^{-2}, while the Simpson dominance index and Pielou evenness index showed gradually decreasing trends. The Margalef richness index and Shannon-Wiener diversity index of the herb layer peaked at a stand density of 2450 trees · hm^{-2}, while the Simpson dominance index and Pielou evenness index peaked at 1950 trees · hm^{-2}. (4) The similarity of species composition among understory communities in *R. pseudoacacia* forests of different densities was above the medium similarity level. When the stand density was 1950–2450 trees · hm^{-2}, the understory community species diversity of *R. pseudoacacia* plantation was optimal, which was conducive to im-

proving and sustaining its ecological function.

Keywords: stand density; *Robinia pseudoacacia* plantations; community structure; species diversity; loess region of western Shanxi Province

Introduction

Forests are among the most important ecosystems on Earth, characterized by complex community structures and rich biodiversity, serving as critical sites for plant growth and energy exchange. Plant species diversity, as an essential component of biodiversity, represents a key indicator of plant community structure. It not only reflects differences in community composition, structure, and function, but also characterizes the relationships between communities and environmental factors under different natural geographical conditions. The shrub and herb community, as an important component of forest ecosystems, plays a vital role in maintaining species diversity and plantation stability. Therefore, how to reasonably maintain and improve understory species diversity is of great significance for forest management and ecological restoration.

Understory species diversity is influenced by many factors, including stand density, stand age, and stand configuration. Among these, stand density, as an important structural characteristic, can accelerate tree differentiation and community succession, thereby affecting understory species diversity. Previous studies have reported varying effects of stand density on understory species diversity. For example, Ashfaq et al. studied understory species diversity in *Pinus massoniana* plantations of different densities in Hubei Province, finding that lower density stands (500–800 trees $\cdot$ hm^{-2}) had higher shrub and herb diversity, with herb layer species richness exceeding that of the shrub layer. Liu et al. studied understory species diversity in *R. pseudoacacia* plantations in the loess region and found that species diversity indices decreased with increasing stand density. Wang et al. investigated understory species diversity in *Cypress funebris* plantations of different densities in Sichuan Province and concluded that understory species diversity was optimal at a stand density of 1200–1600 trees $\cdot$ hm^{-2}. Yun et al. studied understory plant community diversity under different stand types and densities in the loess region of western Shanxi and found that species diversity was best at a stand density of 1200–1600 trees $\cdot$ hm^{-2} for natural secondary forests and mixed plantations. These inconsistent conclusions indicate that the relationship between stand density and understory species diversity requires further investigation.

The Loess Plateau, located in the middle reaches of the Yellow River, suffers from severe soil erosion and is a typical ecologically degraded region. Since the 1970s, large-scale vegetation restoration has been implemented on the Loess Plateau, forming a relatively complete protective forest system that has played an important role in controlling soil erosion and improving the ecological environment. *Robinia pseudoacacia*, due to its strong adaptability and drought tolerance, has been widely planted as a soil and water conservation tree species on the

Loess Plateau. The Caijiachuan watershed in Jixian County, Shanxi Province, established large areas of *R. pseudoacacia* plantations in the 1980s. However, with the growth of these plantations and increasing water consumption, problems such as small growth increments and low ecological service functions have become prominent. Therefore, determining optimal afforestation and management densities based on species diversity and conducting tending management of soil and water conservation forests can ensure high-quality development and sustainable ecological service functions in the loess region. This study takes artificial *R. pseudoacacia* plantations of different densities in the Caijiachuan watershed of western Shanxi as the research object. Through field plot surveys, we analyzed the composition characteristics, growth characteristics, and species diversity indices of understory plant communities in *R. pseudoacacia* plantations, examined the relationship between stand density and understory species diversity, and determined appropriate management densities for soil and water conservation forests, aiming to provide a reference for improving ecological functions and promoting sustainable development of *R. pseudoacacia* plantations on the Loess Plateau.

1.1 Study Area Overview

The study area is located in the Caijiachuan watershed (36°14 27 -36°18 23 N, 110°39 45 -110°47 45 E), where the Jixian National Forest Ecosystem Observation and Research Station is situated. This watershed is a third-level tributary of the Yellow River, representing a typical loess hilly and gully region with a warm temperate semi-arid continental climate. The average altitude is 1172 m, with an average annual precipitation of 579 mm (showing large interannual variation and frequent heavy rains during the flood season) and an average annual temperature of 9.9°C. The frost-free period averages 150 days. The soil type is cinnamon soil with loess parent material. The main artificial forests in the Caijiachuan watershed are *R. pseudoacacia*, *Pinus tabuliformis*, and *Platycladus orientalis*. Understory vegetation is dominated by species from Rosaceae, Gramineae, and Caprifoliaceae families, with representative species including *Rosa xanthina*, *Spiraea pubescens*, *Rubus parvifolius*, *Artemisia gmelinii*, *Artemisia selengensis*, *Phalaris arundinacea*, and *Syringa oblata*.

1.2.1 Sample Plot Setup and Investigation

Typical artificial *R. pseudoacacia* plantations with good growth conditions, complete stand structure, and uniform stand age (35 years) were selected in the Caijiachuan watershed. Six stand densities were investigated: 950, 1450, 1950, 2450, 2950, and 3450 trees $\cdot$ hm^{-2}. Three 20 m × 20 m sample plots were established for each density, totaling 18 plots. Slope aspect, altitude, and slope gradient were consistent across plots. In each plot, all trees were measured for height, diameter at breast height (DBH), crown width, and number of individuals. Within each standard plot, five 5 m × 5 m shrub quadrats were set up at the four corners and center, and five 1 m × 1 m herb quadrats were established within each shrub quadrat, resulting in 25 herb quadrats per plot. The name, number, height, and coverage of shrubs and herbs in each quadrat were recorded. Lianas and tree seedlings (height < 2 m) were recorded in the shrub layer. Geographic coordinates, slope aspect, and altitude were measured using GPS. Basic plot information is shown in .

1.2.2 Aboveground Biomass Measurement of Shrubs and Herbs

The "whole-plant harvest method" was used in shrub and herb quadrats within each plot. All aboveground parts in the quadrats were harvested and weighed for fresh weight. Samples were placed in sealed bags and taken to the laboratory, then dried in an oven at 85°C to constant weight. The dry weight was recorded, and biomass was calculated for each plot.

1.2.3 Species Diversity Measurement

The important value (IV), Margalef richness index (R), Shannon-Wiener diversity index (H), Simpson dominance index (D), Pielou evenness index (Jsw), and Jaccard similarity coefficient (q) for shrub and herb layers were calculated following reference [27]. The formulas are:

Important Value (IV):

$$IV = (Rd + Rf + Rc)/3$$

Relative density (Rd):

$$Rd = \frac{Ni}{N} \times 100\%$$

Relative frequency (Rf):

$$Rf = \frac{Fi}{F} \times 100\%$$

Relative coverage (Rc):

$$Rc = \frac{Ai}{A} \times 100\%$$

Margalef richness index (R):

$$R = \frac{S - 1}{\ln N}$$

Shannon-Wiener diversity index (H):

$$H = -\sum_{i=1}^{S} P_i \ln P_i$$

Simpson dominance index (D):

$$D = 1 - \sum_{i=1}^{S} P_i^2$$

Pielou evenness index (Jsw):

$$Jsw = \frac{H}{\ln S}$$

Jaccard similarity coefficient (q):

$$q = \frac{a}{a+b+c}$$

Where Rd, Rf, and Rc are relative density, relative frequency, and relative coverage; S is the total number of species in the quadrat; Pi is the relative number of individuals of species i (Ni/N); N is the total number of individuals of all species; Ni is the number of individuals of species i; Fi is the frequency of species i; Ai is the coverage of species i; a is the number of species shared by two communities; b is the number of species unique to community 1; c is the number of species unique to community 2. Similarity levels are defined as: $0.00 \leq q < 0.25$ (extremely dissimilar), $0.25 \leq q < 0.50$ (moderately dissimilar), $0.50 \leq q < 0.75$ (moderately similar), and $0.75 \leq q \leq 1.00$ (extremely similar).

1.2.4 Data Processing

Excel 2019 was used for data organization, Origin 2017 for graphing, and SPSS 23.0 for statistical analysis. One-way ANOVA was used to test differences in characteristic indices among different stand densities, with the least significant difference (LSD) method for multiple comparisons.

2.1 Understory Plant Community Species Composition

[Figure 2: see original paper] shows the species composition of understory plant communities in *R. pseudoacacia* plantations of different densities. A total of 77 plant species were recorded across the six stand densities, including 36 shrub species and 41 herb species. Rosaceae had 14 species, Gramineae had 11 species, and Caprifoliaceae had 4 species, accounting for 18.18%, 14.29%, 5.19%, and 3.90% of the total species, respectively. Both shrub and herb layer species numbers showed a trend of first increasing and then decreasing with stand density. Shrub layer species number peaked at 19 species when stand density was 1950 trees · hm^{-2}, while herb layer species number peaked at 24 species at 2450 trees · hm^{-2}. The total number of shrub and herb species reached a maximum of 39 species at 1950 trees · hm^{-2} and a minimum of 28 species at 3450 trees · hm^{-2}.

presents the important values of understory community species. The main dominant shrub species were *Rubus parvifolius*, *Rosa xanthina*, *Periploca sepium*, and *Syringa oblata*, while the main dominant herb species were *Phalaris arundinacea*, *Artemisia gmelinii*, and *Carex onoei*. When density was below 1950 trees $\cdot$ hm^{-2}, *Rubus parvifolius* was the dominant shrub species, with *Rosa xanthina* as the main associated species. At 1950 trees $\cdot$ hm^{-2}, *Rosa xanthina* became the dominant species. At 2450 trees $\cdot$ hm^{-2}, *Sophora davidii* became the dominant species with an important value of 51.35%. In the herb layer, when density was below 1950 trees $\cdot$ hm^{-2}, *Phragmites australis* had the highest important value (31.63%), likely due to better soil moisture conditions. At 2450 trees $\cdot$ hm^{-2}, the important value of *Phalaris arundinacea* reached 52.21%. The results indicate that dominant shrub species in *R. pseudoacacia* plantations under different densities were mainly heliophytic and mesophytic plants, while dominant herb species were mainly mesophytic and shade-tolerant species with strong adaptability.

2.2 Understory Plant Community Growth Characteristics

[Figure 3: see original paper] shows the growth characteristics of understory plant communities. With increasing stand density, the average height of the shrub layer gradually decreased, reaching 206 cm at 950 trees $\cdot$ hm^{-2} and 103 cm at 3450 trees $\cdot$ hm^{-2}. Shrub layer biomass decreased with increasing stand density, reaching a maximum of 94.64 g $\cdot$ m^{-2} at 950 trees $\cdot$ hm^{-2}, which was significantly higher than other densities ($P < 0.05$). The total coverage of shrub and herb layers showed little change across different stand densities, with no significant differences ($P > 0.05$), but reached 40.33% at 950 trees $\cdot$ hm^{-2} and 38.67% at 2450 trees $\cdot$ hm^{-2}. Herb layer biomass showed small fluctuations among stand densities with no significant differences ($P > 0.05$), reaching a maximum of 31.29 g $\cdot$ m^{-2} at 2450 trees $\cdot$ hm^{-2}. Total shrub and herb biomass was highest at 950 trees $\cdot$ hm^{-2} (117.82 g $\cdot$ m^{-2}) and lowest at 3450 trees $\cdot$ hm^{-2} (29.47 g $\cdot$ m^{-2}).

2.3 Understory Plant Community Species Diversity Characteristics

[Figure 4: see original paper] illustrates the species diversity indices. With increasing stand density, the Margalef richness index and Shannon-Wiener diversity index of the shrub layer showed a trend of first increasing then decreasing, peaking at 1950 trees $\cdot$ hm^{-2}, while the Simpson dominance index and Pielou evenness index gradually decreased. For the herb layer, the Margalef richness index and Shannon-Wiener diversity index peaked at 2450 trees $\cdot$ hm^{-2}, while the Simpson dominance index and Pielou evenness index peaked at 1950 trees $\cdot$ hm^{-2}. No significant differences were found among stand densities for any of these indices ($P > 0.05$).

2.4 Understory Plant Community Similarity

shows the similarity coefficients among communities. Understory plant communities in *R. pseudoacacia* plantations of different densities showed high similarity, with all Jaccard coefficients q $\geq$ 0.50 (moderately similar or higher). The highest similarity (q = 0.86, extremely similar) occurred between densities of 2450 and 2950 trees $\cdot$ hm^{-2}, while the lowest similarity (q = 0.53, moderately similar) occurred between 950 and 3450 trees $\cdot$ hm^{-2}, and between 1450 and 3450 trees $\cdot$ hm^{-2}. This indicates that high-density communities in the Caijiachuan watershed had more similar understory species composition, while low-density and high-density communities showed lower similarity.

3 Discussion

This study recorded 36 shrub species and 41 herb species across *R. pseudoacacia* plantations of different densities. With increasing stand density, the number of families and genera in both shrub and herb layers showed a trend of first increasing then decreasing, with the highest species numbers occurring at medium densities. This aligns with Li et al., who suggested that excessively high stand density intensifies interspecific competition, while excessively low density allows *R. pseudoacacia* to occupy more water, heat, and light resources, suppressing shrub and herb development. Therefore, both excessively high and low stand densities are unfavorable for shrub and herb community development. When density exceeded 2950 trees $\cdot$ hm^{-2}, shrub species number decreased rapidly while herb species number decreased more slowly, indicating that this density level limited shrub survival but had less impact on herbs, consistent with Zhang et al. From a species diversity conservation perspective, a stand density of 1950–2450 trees $\cdot$ hm^{-2} is appropriate for maintaining relatively high species numbers in both layers.

Dominant and associated species reflect community structure and dynamics. At low densities, dominant shrub species were mainly light-demanding species such as *Cotinus coggygria* and *Abelia biflora*, with deciduous small tree seedlings including *Koelreuteria paniculata*, *Acer stenolobum*, *Ulmus pumila*, *Crataegus pinnatifida*, and *Amygdalus davidiana* growing well. Herb layer dominants were mainly Gramineae species such as *Phalaris arundinacea* and *Lolium perenne*. At 2450 trees $\cdot$ hm^{-2}, *Phragmites australis* appeared as a dominant species, indicating that medium-density stands had more suitable soil moisture conditions favorable for succession from pure to mixed stands. With increasing stand density, canopy closure increased, reducing light availability. Mesophytic shrubs such as *Syringa oblata*, *Forsythia suspensa*, *Periploca sepium*, and *Spiraea pubescens* gradually became dominant, while Compositae species led by *Artemisia gmelinii* became co-dominant with Gramineae in the herb layer. At densities above 2950 trees $\cdot$ hm^{-2}, environmental conditions changed, becoming unsuitable for water-consuming plants. The important value of *Rubus parvifolius* decreased, while drought-tolerant species such as *Sophora davidii* and *Ziziphus jujuba* increased in importance, potentially replacing Rosaceae species.

Shade-tolerant herbs such as *Solanum septemlobum*, *Stellaria palustris*, and *Humulus scandens* became dominant. Thus, high stand density creates poor light and water conditions, causing stress-sensitive species to decline while drought-tolerant, adaptable species become dominant.

Shrub and herb species were concentrated in Rosaceae, Caprifoliaceae, Gramineae, and Compositae, indicating strong adaptability of these families to arid environments. *Rubus parvifolius* was distributed across all densities as a dominant or sub-dominant species, suggesting it is a key suitable species in this region. Other widely distributed species including *Rosa xanthina*, *Cynanchum bungei*, *Periploca sepium*, *Ailanthus altissima*, *Syringa oblata*, *Phalaris arundinacea*, *Carex onoei*, *Artemisia gmelinii*, and *Artemisia carvifolia* showed good adaptation to different stand densities and should be prioritized in vegetation restoration in the loess region.

We analyzed height, coverage, and aboveground biomass to characterize growth responses to stand density. Increased vegetation height, coverage, and biomass can enhance rainfall interception and reduce splash erosion, benefiting soil conservation and water retention. Although stand density effects on growth characteristics were not significant, density directly affects light distribution and indirectly influences understory growth. In the Caijiachuan watershed, low-density stands had significantly higher total community biomass and shrub layer biomass than other stands, consistent with previous research. Shrub layer average height and total community biomass decreased with increasing stand density, reaching maxima at 950 trees $\cdot$ hm^{-2}. This occurs because low-density stands have smaller canopy closure, providing better light and nutrient conditions for understory shrubs. Herb layer biomass showed no clear pattern, likely because herbs receive even less light than shrubs and can better adapt to environmental changes. Chen et al. suggested that herbs are mostly stress-tolerant and can adapt well to environmental changes. As stand density increases, canopy closure limits light, affecting plant growth and reducing shrub height and total biomass. Total shrub and herb coverage showed small fluctuations without significant differences among densities, similar to previous findings.

Overall, understory species diversity was optimal at stand densities of 1950–2450 trees $\cdot$ hm^{-2}, indicating suitable environmental conditions for stable community structure formation. We recommend 1950–2450 trees $\cdot$ hm^{-2} as the optimal stand density, which is similar to previous findings of 1200–1600 trees $\cdot$ hm^{-2} being suitable for *R. pseudoacacia* plantations. Medium densities better maintain community species diversity and sustainable development. Soil water content is significantly positively correlated with plant height, coverage, and biomass in the 0–100 cm layer. Water resources are scarce in the loess region, with deep groundwater tables, making soil moisture a key factor limiting plant growth. Excessively high stand density can cause excessive soil water consumption, affecting plant development.

Except for the Margalef index, the other three diversity indices were relatively low, indicating that understory plant community structure in the Caijiachuan watershed is relatively simple and unstable. The Margalef and Shannon-Wiener indices peaked at 1950 trees · hm^{-2} for the shrub layer and at 2450 trees · hm^{-2} for the herb layer, showing that medium-density stands had the richest species composition and highest diversity. This may be because mesophytic and shade-tolerant species increased at medium densities. The Simpson and Pielou indices of the shrub layer decreased with increasing stand density, indicating lower habitat uniformity and reduced dominance of dominant species at higher densities. Lower stand density enhanced photosynthesis and increased available space, resulting in better plant growth and more uniform distribution. Herbs can adapt more quickly to environmental changes than shrubs in high-density stands, showing higher diversity and more uniform distribution. Shu et al. studied *Cunninghamia lanceolata* plantations and found that shrub layer Pielou index decreased with increasing stand density, consistent with our results.

4 Conclusion

(1) A total of 77 plant species were recorded across six stand densities, including 36 shrub species and 41 herb species. Rosaceae, Compositae, Gramineae, and Caprifoliaceae were the most species-rich families. Shrub layer species number peaked at 1950 trees · hm^{-2}, while herb layer species number peaked at 2450 trees · hm^{-2}.

(2) Dominant species in *R. pseudoacacia* plantations changed significantly with stand density, showing a successional pattern from heliophytic to mesophytic to shade-tolerant species as density increased.

(3) Shrub height and biomass decreased with increasing stand density, while herb biomass showed no significant differences among densities ($P > 0.05$). Total shrub and herb coverage changed little across densities.

(4) Except for the Margalef richness index, the other three diversity indices showed no significant differences among stand densities. Understory community species diversity was optimal at stand densities of 1950–2450 trees · hm^{-2}.

References

[1] Guo Wenyue, Shen Wenxing. Value formation mechanism and evaluation method of forest plant species diversity[J]. World Forestry Research, 2020, 33(4): 118-122.

[2] Li Xing, Xin Zhiming, Dong Xue, et al. β-diversity and interpretation of plant communities in Beishan and Manongshan areas of Dunhuang[J]. Arid Zone Research, 2022, 39(5): 1464-1472.

[3] Manning P, Fons V D P, Soliveres S, et al. Redefining ecosystem multifunctionality[J]. Nature Ecology & Evolution, 2018, 2(9): 427-436.

[4] Gamfeldt L, Roger F. Revisiting the biodiversity ecosystem multifunctionality relationship[J]. Nature Ecology & Evolution, 2017, 1(7): 0168.

[5] Liu Jianli, Li Kairong, Yi Liang, et al. Structure of *Robinia pseudoacacia* plantation and undergrowth plant diversity in the hilly area of the Loess Plateau[J]. Bulletin of Soil and Water Conservation, 2008, 28(3): 49-52, 70.

[6] Qin Wei, Zhu Qingke, Zhang Yuqing, et al. Dynamics of plant community species diversity in the process of ecological rehabilitation in north Shanxi loess area[J]. Chinese Journal of Applied Ecology, 2009, 20(2): 403-409.

[7] Wang Meizhen, Bi Haojie, Jin Suo, et al. Effects of stand density on understory species diversity and soil physico-chemical properties of a *Cypress funebris* plantation in Yunding Mountain[J]. Acta Ecologica Sinica, 2019, 39(3): 981-988.

[8] Shao Ming' an, Jia Xiaoxu, Wang Yunqiang, et al. Review of studies on dried soil layers in the Loess Plateau[J]. Advances in Earth Science, 2016, 31(1): 14-22.

[9] Wang Min, Zhou Runhui, Yu Feiyan, et al. Dynamic changes of *Eucalyptus robusta* understory species diversity and biomass in plantations at different ages[J]. Plant Research, 2021, 41(4): 496-505.

[10] Li Jiangwen, He Bangyin, Li Cai, et al. Differences in species composition and functional diversity of understory plant communities of *Robinia pseudoacacia* L. stands with different ages[J]. Plant Science Journal, 2022, 40(3): 315-323.

[11] Miu Ning, Zhou Zhuli, Shi Zuomin, et al. Succession dynamics of community structure and species diversity after clearcutting of faxon fir (*Abies faxoniana*) forest stands[J]. Acta Ecologica Sinica, 2014, 34(13): 3661-3671.

[12] Yun Huiya, Bi Huaxing, Jiao Zhenhuan, et al. Composition and diversity of understory plants under different stand types and densities in loess region of western Shanxi Province[J]. Journal of Zhejiang Agricultural and Forestry University, 2023, 40(3): 569-578.

[13] Ashfaq A, Dong D, Kashif A, et al. Response of understory vegetation, tree regeneration, and soil quality to manipulated stand density in a *Pinus massoniana* plantation[J]. Global Ecology and Conservation, 2019, 20(6): e00775.

[14] Zhao Yao, Wang Baitian. Plant diversity of different forestland in loess region of western Shanxi Province, northern China[J]. Journal of Beijing Forestry University, 2018, 40(9): 45-54.

[15] Zhang Bowwen, Qin Juan, Ren Zhongming, et al. Effects of slope aspect on understory plant diversity of *Pinus massoniana* pure forest and different coniferous and broad-leaved mixed forest types in north subtropical region[J]. Ecology and Environmental Sciences, 2022, 31(6): 1091-1100.

[16] Burkhart H E. Comparison of maximum size density relationships based on alternate stand attributes for predicting tree numbers and stand growth[J]. Forest Ecology & Management, 2013, 289(38): 404-409.

[17] Li Guolei, Liu Yong, Lv Ruiheng, et al. Respones of understory vegetation development to regulation of tree density in *Larix principis-rupprechtii* plantations[J]. Journal of Beijing Forestry University, 2009, 31(1): 19-24.

[18] Zhang Liuhua, Qi Jinqiu, Liu Pingyu, et al. Effects of stand density on community structure and species diversity of *Eucalyptus robusta* plantation[J]. Acta Botanica Boreali Occidentalia Sinica, 2018, 38(1): 166-175.

[19] Hao Wenfang, Du Feng, Chen Xiaoyan, et al. Composition and diversity analysis of natural communitiy plants in Loess hilly region[J]. Acta Agrestia Sinica, 2012, 20(4): 609-615.

[20] Sun Qianhui, Wu Xia, Wang Meizhen, et al. Effects of stand density on understort species diversity and soil physicochemical properties of *Pinus massoniana* plantation[J]. Chinese Journal of Applied Ecology, 2018, 29(3): 732-738.

[21] Wang Yirui, Wang Yanhui, Duan Wenbiao, et al. Effects of *Robinia pseudoacacia* canopy density on the characters of understory plants in plantations on the Loess Plateau of China[J]. Chinese Journal of Applied Ecology, 2023, 34(2): 305-314.

[22] He Xinyue, Wang Ning, Liu Junyang, et al. The variation of plant community diversity and biomass along a soil water gradient in loess hilly region[J]. Chinese Journal of Ecology, 2021, 40(1): 31-40.

[23] Guo Zhongsheng, Shao Ming' an. Soil water carrying capacity of vegetation and soil desiccation in artificial forestry and grassland in semi-arid regions of the Loess Plateau[J]. Acta Ecologica Sinica, 2003, 23(8): 1640-1647.

[24] Wen Jing, Zhang Qiuliang, Li Jiayue, et al. Effects of intensity on diversity of undergrowth vegetation and biomass of *Larix chinensis* forest[J]. Journal of Central South University of Forestry and Technology, 2019, 39(5): 95-100, 118.

[25] Xu Zhichao. Vegetation Restoration and Plantation Sustainability Assessment on the Loess Plateau: A Case Study of Wuqi Country, Shanxi[D]. Beijing: Beijing Forestry University, 2011.

[26] Qu Hong. Effect of Artificial Forest Construction on Plant Diversity in Shanxi Loess Plateau[D]. Beijing: Beijing Forestry University, 2008.

[27] Chen Conglin, Sun Yimiao, Gong Limei, et al. Community structure and species diversity of *Eucalyptus grandis* plantation with different stand densities in road area[J]. Journal of Forest and Environment, 2022, 42(1): 20-28.

[28] Ding Kai, Zhang Yuting, Zhang Junhong, et al. Effects of Chinese fir plantations with different densities on understory vegetation and soil microbial community structure[J]. Chinese Journal of Plant Ecology, 2021, 45(1): 62-73.

[29] Shu Weiwei, Lu Lihua, Li Hua, et al. Effects of stand density on understory vegetation and soil properties of *Cunninghamia lanceolata* plantation[J]. Acta Ecologica Sinica, 2021, 41(11): 4521-4530.

[30] Chen Jie, Guo Yili, Lu Xunling, et al. Species diversity of herbaceous communities in Yiluo River Basin[J]. Acta Ecologica Sinica, 2012, 32(10): 3021-3030.

[31] Zhao Jiangping. Effects of Mid-aged Forest Density and Tending Years of Artificial *Robinia pseudoacacia* on Stand Composition Structure, Plant Functional Traits and Soil Properties[D]. Yangling: Northwest Agriculture and Forestry University, 2022.

[32] Li Yuting. Study on Characteristics of Typical Vegetation and Soil Moisture Dynamic in the Loess Plateau of Western Shanxi Province[D]. Beijing: Beijing Forestry University, 2021.

[33] Wei Xi. Coupling Relationships between Artificial Stand Structure and Soil and Water Conservation Function in the Loess Region of Western Shanxi[D]. Beijing: Beijing Forestry University, 2018.

[34] Wang Shanshan. Directional Regulation of *Robinia pseudoacacia* Forest Density in the Loess Plateau in Western Shanxi, China[D]. Beijing: Beijing Forestry University, 2021.

Note: Figure translations are in progress. See original paper for figures.

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